Laser Produced Plasma Source System Development

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ABSTRACT

This paper provides a review of development progress for a laser-produced-plasma (LPP) extreme-ultra-violet (EUV) source with performance goals targeted to meet joint requirements from all leading scanner manufacturers. Laser produced plasma systems have been developed as a viable approach for the EUV scanner light source for optical imaging of circuit features at sub-32nm and beyond nodes on the ITRS roadmap. Recent advances in the development of the system, its present average output power level and progress with various subcomponents is discussed. We present the latest results on peak EUV and average EUV power as well as stability of EUV output, measured in burst-mode operation at the nominal repetition rate of the light source. In addition, our progress in developing of critical components, such as normal-incidence EUV collector and liquid-target delivery system is described. We also report on dose stability, plasma position stability and EUV distribution at the output region of the source. This presentation reviews the experimental results obtained on systems with a focus on the topics most critical for an HVM source.

The capability to scale LPP power by further development of the high power CO_2 drive laser in order to increase duty cycle and duration of continuous light source operation is shown. Production systems with thermal management and capable of 5 sr light collection are being assembled and tested. A description of the development of a normal-incidence ellipsoidal collector is included. Improvements in substrate quality lead to increased EUV reflectance of the mirror. Results on the generation of liquid tin droplets as target material for efficient plasma generation are also described. The droplet generator serves as a key element in the precise and spatially stable delivery of small quantities of liquid tin at high repetition rates. We describe a protection module at the intermediate focus (IF) region of the source and imaging of the EUV distribution using a sub-aperture collector and a fluorescent screen. A path to meet requirements for production scanners planned well into the next decade is also presented.

Keywords: EUV source, EUV lithography, Laser Produced Plasma, High Volume Manufacturing

1. INTRODUCTION

EUV Lithography is the front runner for next generation critical dimension imaging after 193 nm immersion lithography below the 32 nm node on the International Technology Roadmap for Semiconductors (ITRS) beginning in 2013. NAND Flash devices are expected to need the manufacturing technology as soon as 2011, with Beta generation systems required for development as early as 2010. The availability of a high power 13.5 nm source has been categorized as high risk and ranked as critical with other technologies requiring significant developments to enable the realization of EUV lithography. High sensitivity photoresists with good line-edge-roughness (LER) and line-width-roughness (LWR) are needed to keep the required source power within reasonable limits. Photoresist sensitivity and other light absorbing elements are the basis to derive EUV source power requirements within the usable bandwidth (BW) of 2 %. According to the joint requirements from scanner manufacturers an EUV power of > 115 W 2 % BW at the intermediate focus (IF) is required for 5 mJ/cm^2 photoresist speed to enable > 100 wph scanner throughput, and 180 W 2 % BW at IF is needed for 10 mJ/cm^2. Photoresist sensitivities above 20 mJ/cm^2 could drive power requirements well above the 200 W level, and the need for a spectral purity filter (SPF) could increase the requirements even higher. A scalable EUV source architecture is needed to enable the evolution of EUV lithography during the life cycle of the technology. Laser-produced-plasma (LPP) sources are expected to deliver the necessary high power for

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critical-dimension high-volume manufacturing (HVM) scanners for the production of integrated circuits in the post-193 nm immersion era.[1]

LPP EUV lithography light sources generate the required 13.5 nm radiation by depositing laser energy at 10.6 micron wavelength into tin (Sn) creating a highly ionized plasma with electron temperatures of several 10's of eV. The energetic radiation generated during the decay of these ions is emitted into all directions. It is collected with a normal-incidence mirror (collector), and focused to an intermediate point from where it is relayed to the scanner optics and ultimately to the wafer. The conversion efficiency (CE) of the laser energy into EUV energy is critical to meeting the required power levels. A prototype configuration based on this approach is described and several recent developments are discussed. The normal-incidence mirror is protected from the plasma by advanced debris mitigation technology. High-energy ions, fast neutrals, and residual source element particles are mitigated to maintain the reflectivity of the collector mirror and enable a long lifetime of this component. Metrology to measure the properties of light at both the plasma and IF are used to qualify the performance of the source.[2]

2. EUV LPP SYSTEM

Our research and development system, described previously[1, 3-5] and shown in Figure 1, serves as the primary tool to test the fundamental capability and longevity of production designs. The performance is monitored by metrology directed at both plasma and at intermediate focus positions. A multi-location witness sample holder at the position of the collector is used to acquire life test data on various MLM samples allowing the effectivity of the debris mitigation and reflectivity of the MLM coatings to be evaluated quantitatively. Alternatively, a sub-aperture collector mirror with 1.6 sr collection angle can be installed. Integrated controls permit semi-automatic operation of the system as well as monitoring and data collection from the various metrology instruments attached to the LPP chamber.

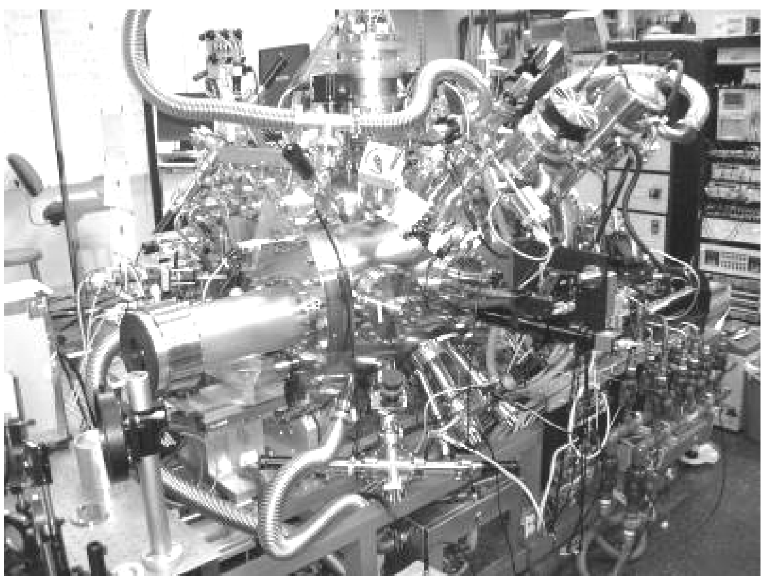

Figure 1: Photograph of the research and development system currently in use.

In the second half of 2007 the preparation of manufacturing space, devoted to EUV purposes was started. New class 10,000 clean-room space construction was completed. Installation of major subsystems was carried out, followed by extensive testing of the drive laser system and other major system components. Several source systems are being assembled; the first production system is expected to be complete by end of 2008. The water-cooled chamber of the production systems is larger in diameter compared to the development system in order to house a 5

sr collector. The optical elements are also water-cooled to enable high-power operation. A photograph of a production system is shown in Figure 2.

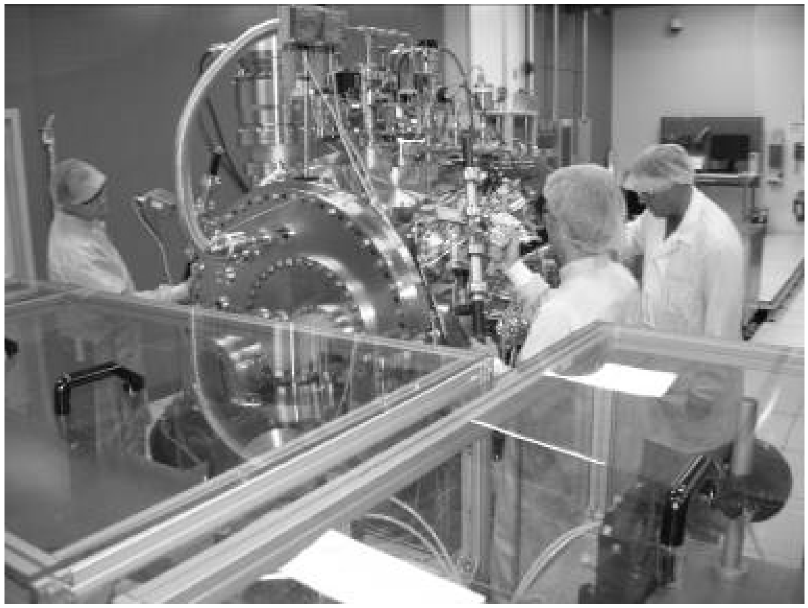

Figure 2: Photograph of production system designed for high average power operation and use of 5 sr collector.

3. RECENT DEVELOPMENT RESULTS

Using the development system shown in Figure 1, the output power performance of the LPP light source was successively improved in terms of average power level by increasing duty cycle and duration of operation through incremental improvement of stability and thermal control.

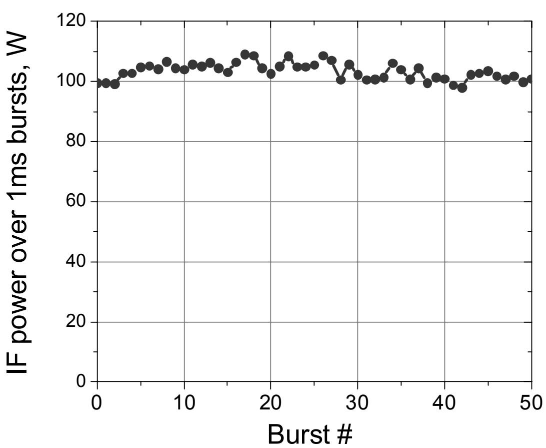

Figure 3: IF-equivalent output power vs. time during 50 kHz burst-mode operation with CO_2 laser focused on 90 μm diameter Sn droplets.

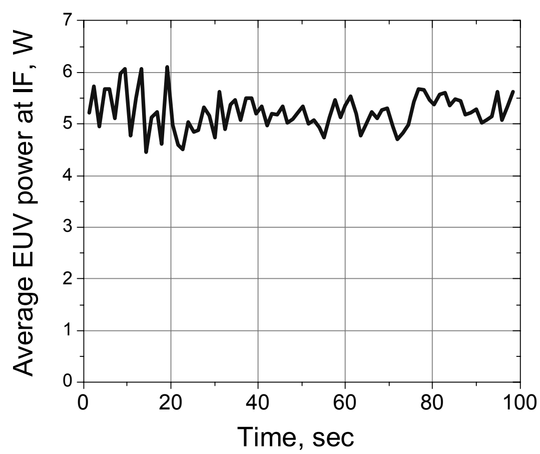

Figure 4: Average EUV power at IF vs. time at 50 kHz repetition rate.

Figure 3 shows an example of EUV power performance achieved using successive bursts of 1 ms duration. The EUV power at plasma is measured with EUV detectors looking at the plasma and then recalculated to equivalent power at the intermediate focus using the following assumptions: 5 sr collector with 50 % reflectivity, and 90 % optical transmission. IF-equivalent burst powers at the 100 W level are routinely achieved. Figure 4 shows similarly calculated average EUV power when the system was running at 5 % duty cycle. In both figures, the system was run without any active control, showing good intrinsic stability. We believe the oscillations in the EUV output power can be easily corrected with the appropriate active control.

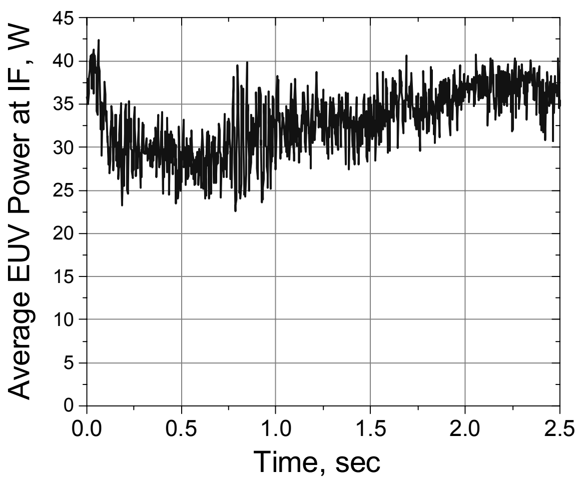

Figure 5: IF equivalent average EUV power vs. time. The laser was operated at 50 kHz, 33% duty cycle.

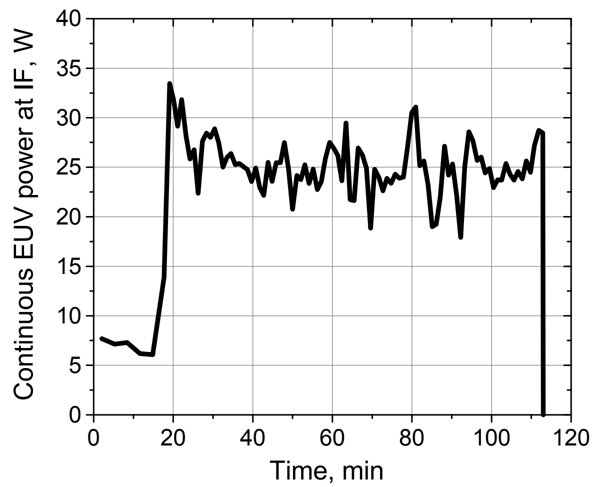

Figure 6: 25 W level IF equivalent average EUV power vs. time at 50 kHz, 30% duty cycle.

In Figures 5 and 6 examples are shown of the system running at higher duty cycles (~ 40%). IF-equivalent average powers above 35 W using similar assumptions for collector and optical transmission were reached. Initially, time limitations for extended operation at high duty cycles were on the order of several seconds. Optical components not actively cooled with operation under these power levels can lead to the formation of thermal lenses in the optics used. Thermal limitations at these duty cycles were overcome, and extended operation of the EUV source for 1.5 hours was demonstrated. Figure 6 shows the continuous average EUV power of 25 W (IF equivalent) could be sustained over extended durations. Presently, the development system is limited in the amount of time the existing system can be run at high duty cycles. The new production systems are capable of high-duty cycle operation for extended time periods and are presently being optimized for high-power operation at ~40% duty cycle, with a ultimate target of 100%.

Figure 7 shows the total accumulated EUV dose at IF determined from the measured EUV power at plasma using standard assumptions during 24 hours of run time. In this period, almost 1 MJ of accumulated dose was reached with the light source. Such a dose level corresponds to the exposure of a batch of approximately 250 wafers of 300 mm size. The dose accumulation was achieved over three consecutive days with ~8 hours of operation per day.

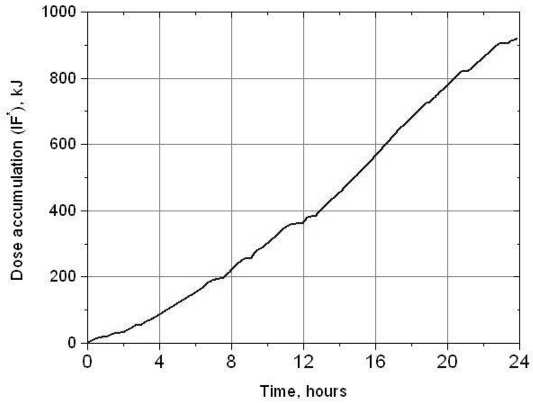

Figure 7: Accumulated dose achieved at IF during 24 hours of run time.

4. NORMAL INCIDENCE COLLECTORS

Cymer's LPP EUV source employs near-normal-incidence mirrors with a very large solid angle for light collection. Such a geometry has numerous advantages, which have been discussed elsewhere.[1,6,7] As we reported last year[1], the complete infrastructure is in place for manufacturing of large-size normal-incidence collector mirrors. For demonstration of the light collection capabilities of our source several 1.6 sr sub-aperture versions (300 mm optical diameter) have been produced and are currently used in our development system for testing. The first large substrates (> 650 mm diameter) of the full HVM design with 5sr collection are now at the final stages of polishing reaching surface roughness levels below 0.4 nm. Figure 8 shows a picture of the first large collector substrate and Figure 9 illustrates optical metrology data obtained by interference measurements.

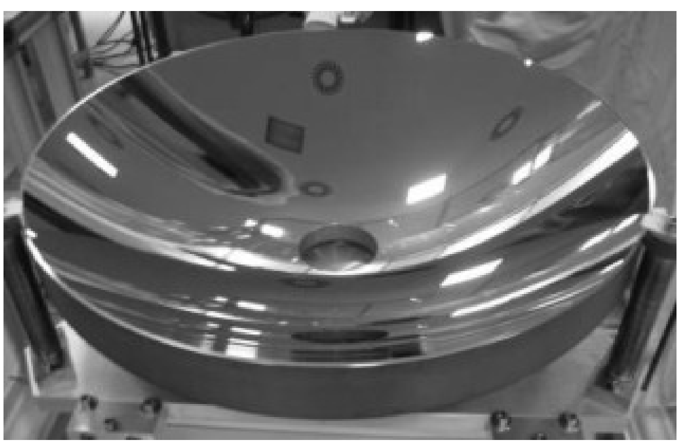

Figure 8: Picture of 5 sr collector mirror after completion of polishing work.

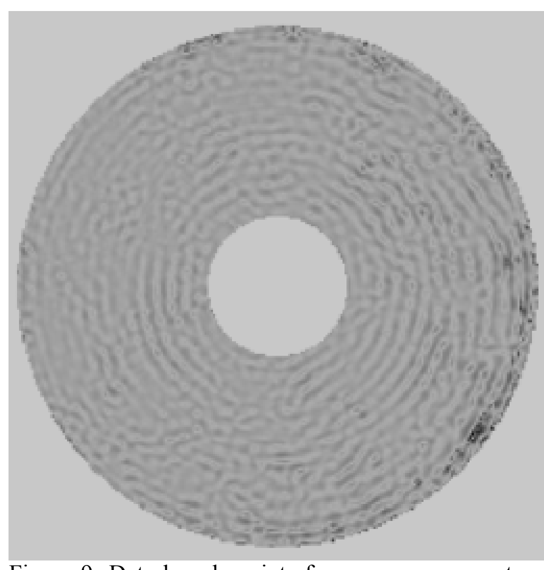

Figure 9: Data based on interference measurements of the optical surface of a 5 sr collector mirror.

Significant development efforts were devoted towards improvements of the EUV reflectivity in order to support a 50 % target value for HVM production. Tremendous progress has been made in several production steps, including substrate manufacturing, polishing, and multilayer coating. Reflectivity curves for a 1.6sr coated collector are presented below

(Figure 10). Improvements of the surface quality of the mirror blank and optimization of the coating process led to 56 - 57 % EUV peak reflectance measured for the graded high-temperature ML coating for s-polarized light. It corresponds to about 52 % area-weighted average in-band EUV reflectance for un-polarized light. A small loss (a few percent) of reflectivity is expected for HVM-type collectors due to the further departure from normal incidence at the outer regions of the mirror,. Further improvement are expected to increase the average reflectivity to >60%.

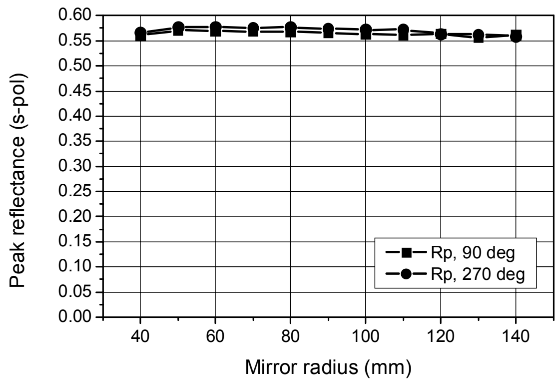

Figure 10: Improved EUV reflectance of a 300 mm diameter high-temperature collector**.** Measurements were carried out at PTB, Berlin.

5. DROPLET GENERATOR

The droplet generator provides liquid tin targets (droplets) to the focal point of the collector where the CO_2 laser pulse is used to create the light-emitting plasma. The main requirement for the generators is to produce small droplet targets at the repetition rate of the laser pulses (typically 50 kHz).[8] Temporal and spatial stability of droplets has been consistently produced over hundreds of hours of operation, with the duration limited by the capacity of the tin reservoir vessel. The longest continuous run of the droplet generator achieved so far is >500 hours. Figure 11 shows timing stability of 50 μm diameter droplets. The standard deviation of the average time between two droplets measured with optical trigger is 86 ns which corresponds to 0.4 % of the nominal period of 20 μs. Short term position stability is better than 1 μm. The position drift observed in Figure 12 (7.3 μm/min) is slow and can be compensated by active position control system. We have also developed the technology for generation of droplets with diameter of ~30 μm. These droplets meet stability and timing requirements for the present system. For second generation sources the droplet diameter will be further reduced to approximately 10 μm.

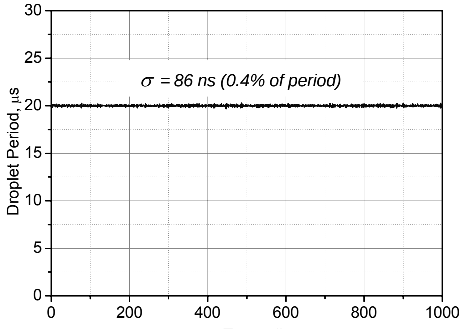

Figure 11: Timing stability of 50 μm droplets.

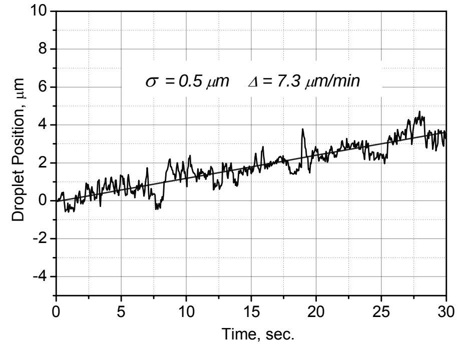

Figure 12: Droplet position stability of 50 μm droplets.

6. IF PROTECTION MODULE

The EUV plasma source may produce debris which may contaminate optics in the illuminator. For protection of illuminator from the debris we developed an IF protection module which uses a gas curtain and differential pumping. The module was tested with surrogate gases. Pressure of contaminants was measured with an RGA in front and behind the module. Suppression was defined as ratio of initial partial pressure of the testing gas in the source chamber to the measured pressure in scanner chamber behind IF. Figure 13 shows the variation of suppression with gas flow rate. The detection limit of 5 orders of magnitude is reached at flow rates several times smaller than maximum allowable. We expect that this suppression can be extrapolated to high values for the full flow rate.

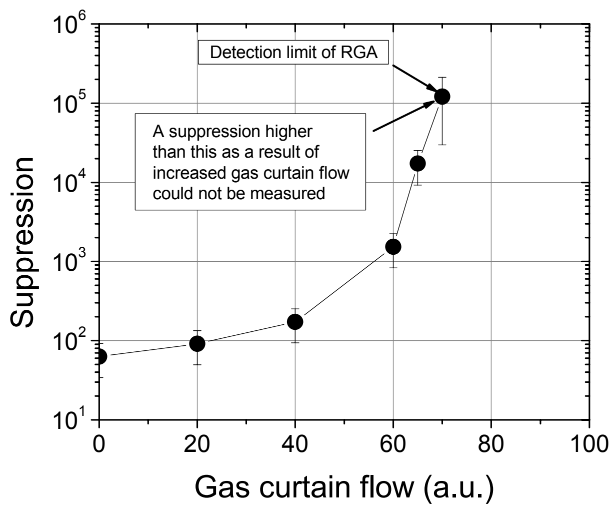

Figure 13: Variation of suppression factor with gas curtain flow rate for the developed IF protection module.

7. EUV ENERGY STABILITY

Figure 14 shows the results for the open-loop energy stability. No active adjustment of droplet stream or the laser beam position on the droplets was done. Furthermore, the RF power (pumping energy) applied to the laser was kept fixed. The ~1 minute-period fluctuations of the output energy are related to a slow shift of the beam position on the droplet targets and are easily correctable. Without any correction, the dose stability is about 1.5%. This shows a good intrinsic stability of the system. With the proper active control, we expect to meet the dose stability numbers that would be required for the production tool.

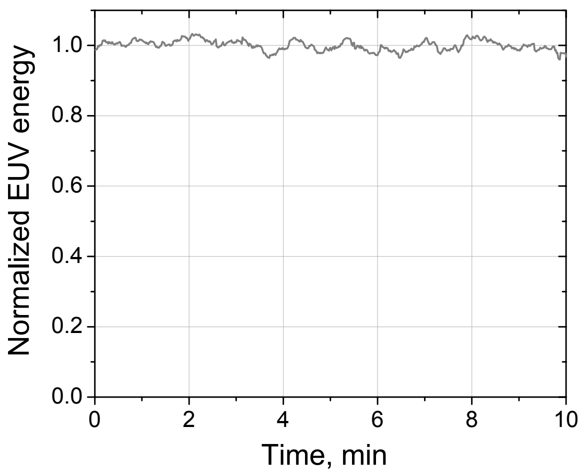

Figure 14: EUV dose stability.
100 W bursts at 50 kHz operation,
Dose stability = ~1.5 %,
(1 sigma, open-loop operation),
500 pulses window.

Figure 15 shows the variation of the average burst EUV output intensity calculated at IF using standard assumption during an 8 hour long run of the system at 8% duty cycle. The recorded power remains at stable level during the entire run indicating the high stability of all elements including laser, focusing optics, alignment elements, droplet generator, and diagnostic tools. Strong variations of the power at the end of the run and after about 2 hours are related to experiments with intentional system misalignment that were carried out during the experiment.

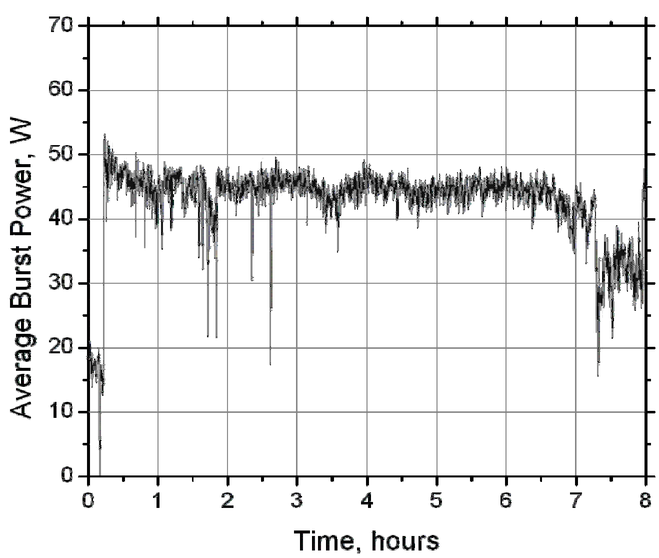

Figure 15: Power variation at IF during long-term operation of LT1 at 8% duty cycle.

8. EUV IMAGE SIZE AND POINTING STABILITY MEASUREMENTS AT PLASMA

The size of the EUV emitting region of the plasma plays a critical role since a source with small etendue supports a large solid angle of light collection and can lead to several advantages in the illumination design. For dose stability, imaging stability and uniformity it is required that the plasma source is located at a fixed position in space with low variations during operation. In order to determine the spatial properties of the in-band EUV emission we have used a pinhole camera arrangement. As described in more detail previously[2], a Zr foil (0.2 nm thick) and a Mo/Si multilayer mirror are introduced in the configuration as spectral bandpass filters for EUV radiation between the pinhole (40 µm diameter) and the backside-illuminated CCD camera (array of 512 x 512 pixels of 24 µm size). The pinhole camera

records predominantly in-band EUV radiation and is mounted with its optical axis oriented perpendicularly to the CO_2 laser beam direction. All pulses within a laser burst are integrated during recording. The camera has a read-out frequency of a few Hz, depending on the chosen size of the imaging array. Figure 16 shows an image obtained for a burst of 50 pulses at 50 kHz repetition rate. For these operating conditions the average source image is nearly spherical. Its width is approximately 90 µm (FWHM) or ~210 µm ($1/e^2$ width). Also shown is an intensity profile of this image along the x-direction of the camera reference frame obtained by averaging over the y direction.

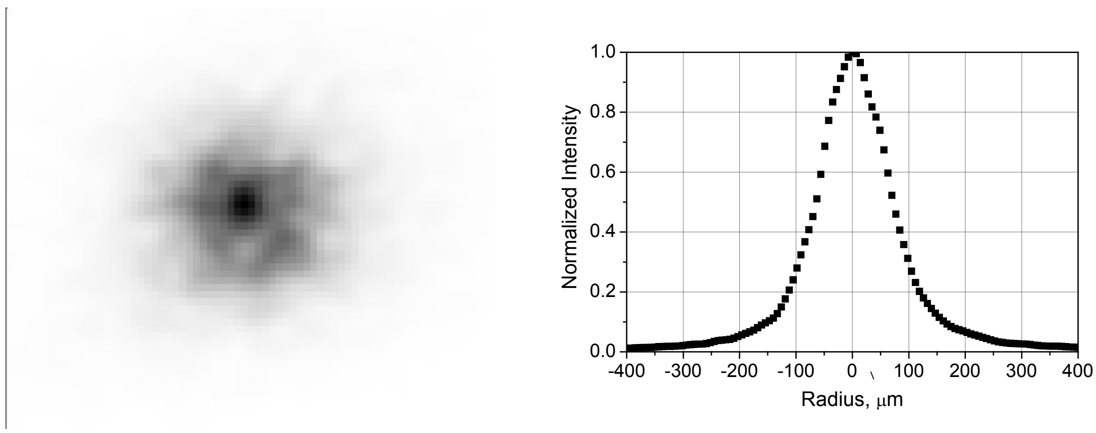

Figure 16. In-band EUV pinhole image of laser-plasma source and corresponding averaged intensity profile.

Information on the position stability of the EUV emitting plasma region can be gathered by capturing successive pinhole images during low-duty cycle operation of the source. Therefore, EUV images were recorded for sets of 100 consecutive bursts of 50 pulses each. Figure 17 displays the results for the *x* and *y* coordinates of intensity-weighted image center positions for 100 bursts recorded during open-loop operation of the source. The 1σ standard deviations are 7.0 µm and 5.0 µm, respectively. Also shown is a corresponding *x-y* scatter plot of the data indicating that the majority of center positions are clustered in a region of about 25 µm in diameter. Long-term drifts of the source position are eliminated by control loops of the droplet stream.

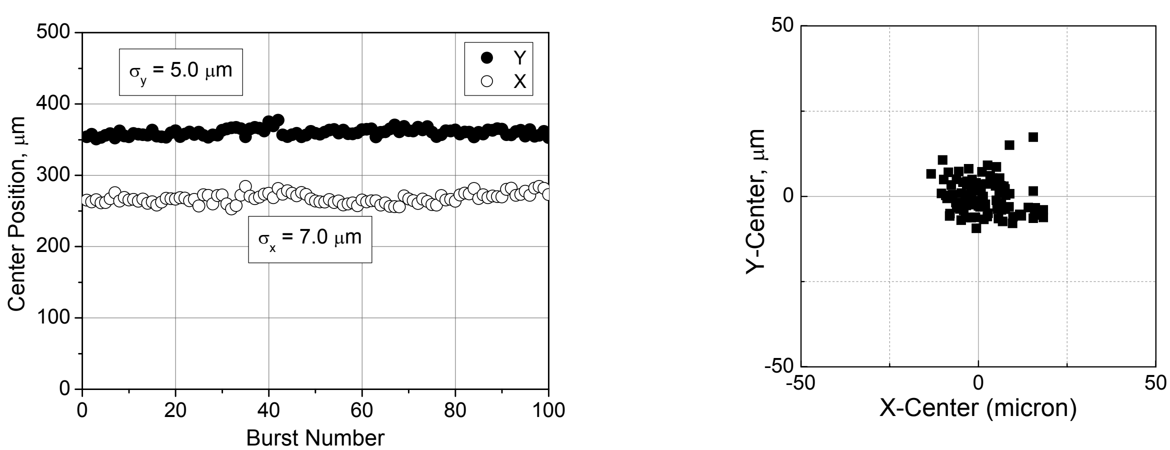

Figure 17: Stability of Source Position.
100 consecutive burst images were recorded with the in-band pinhole camera. Left figure: x and y intensity center position versus burst number. Right figure: corresponding x-y scatter plot of center position.

9. IF IMAGING

The efficient way to collect EUV light from a source is to use a collector in a shape of a section of a prolate spheroid. The through-focus cross-section of such a collector has an elliptical shape. The plasma producing EUV light is located in one focus of the spheroid and light is collected in the other focus. This second focus commonly named Intermediate Focus (IF) is a convenient point to connect an EUV source to the lithography tool. It is also a place where the main source parameters are specified. The normal incidence collector allows for the use of a large solid angle of radiation collection with a single reflection. Current design for an HVM source is complete for the collection angle of 5 sr. A high-temperature multilayer coating is developed[6]. This allows operation of the collector at elevated temperatures, which is advantageous for power handling and in-situ cleaning of coatings. The full scale 5sr collector is being produced with a completion date near the end of 2008[5]. Before the final collector is available, many design verification and performance tests can be done on a smaller size collector.

Behind the IF region several important measurements of EUV irradiation can be performed. When recorded at a distance of several centimeters behind IF, the EUV intensity distribution can provide information on source power, angular distribution and related stability, as well as reflectivity of the collector mirror and collector defects. This plane represents a far field (FF) distribution of EUV radiation. The shape and intensity of EUV distribution can also be used for precise positioning of the EUV source in the focal point of the collector. A schematic setup of such diagnostic is shown in Figure 18. A fluorescent converter screen is placed behind IF, and the emerging visible radiation is monitored with a CCD video camera. Using a fluorescent converter with a short fluorescent time (~70ns) allows measurements at high repetition rates. Figure 19 presents a typical image obtained with a CCD video camera.

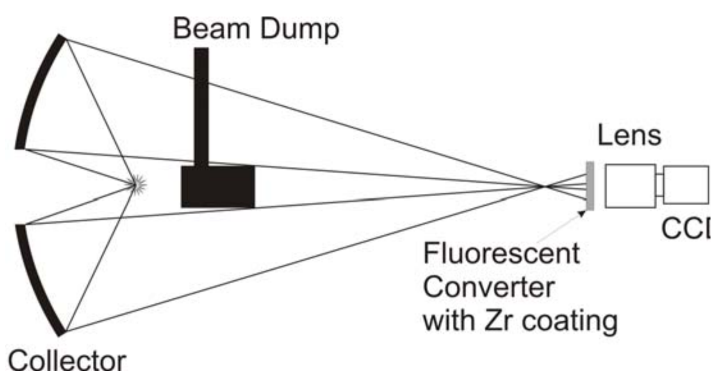

Figure 18: Scheme of Far Field measurements and FF EUV Image.

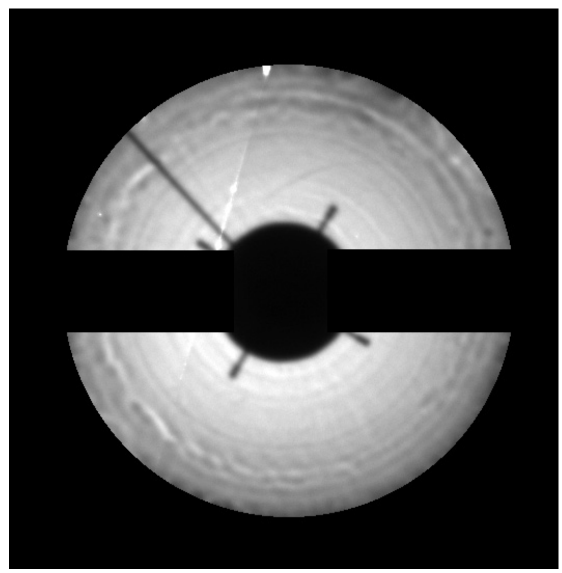

Figure 19: EUV image on fluorescent screen. No EUV reflectivity degradation was observed during 8 hours of operation.

10. ROADMAP

The LPP source roadmap is shown in Figure 20. The pilot product is expected to meet requirements for pre-production or beta generation scanners in 2009 with in-band EUV output power of > 100 W using a 11 kW CO_2 laser system on Sn droplets with 3.0 % CE. The normal-incidence collector used will have ~ 5 sr of light collection with a coating with an EUV reflectivity > 60 % on average over the surface. Transmission losses due to absorption and debris mitigation

techniques are projected to be less than 20 %. It is expected that requirements for later generation LPP EUV sources will drive source power above the 200 W level (HVM I, HVM II) with CO_2 laser technology delivering >20 kW of power. Improvements in CE and collection efficiency should provide additional gain to counter losses due to transmission and obscurations so that power levels exceeding 400 W at IF can be reached.

EUV Source Power Roadmap			
	Pilot	HVM I	HVM II
Drive laser power (kW)	**11**	**19**	**>20**
In-band CE (%)	3.0	3.5	4.0
Collection Efficiency (sr)	5	5.2	5.5
Collector Reflectivity (%)	>60	>60	>60
Optical Transmission (%)	80	85	90
Total EUV power at IF (W)	**>100**	**>200**	**>400**

Figure 20: Projected LPP EUV source roadmap.

11. SUMMARY

Laser-produced plasma has been shown to be the leading source technology with scalability to meet requirements from leading scanner manufacturers and provide a path toward higher power as the lithography tools evolve over their life cycle. EUV average power exceeding 35 W at intermediate focus has been reported and runs with up to 8 hours of stable source operation have been demonstrated. Using a sub-aperture collector mirror, the far-field image of the EUV distribution and collector reflectivity behind IF was recorded, showing no degradation over 8 hours of operation. Normal-incidence collector mirrors of diameter > 650mm and > 5 sr of light collection are in process of being manufactured. Full scale LPP EUV source system manufacturing has begun. The high-conversion-efficiency combination of 10.6 µm laser radiation and Sn source element has been shown with CE in excess of 3 %. The high CE values in our roadmap allow high EUV power at relativity low laser power to enable low cost operation. EUV lithography is expected to be the critical dimension imaging solution post 193 nm immersion in 2011. LPP source technology with power levels exceeding 400 W is expected to enable the IF power requirement projected in the future, and to provide the much needed margin for photoresist sensitivity, spectral purity filters, optics degradation, process latitude, and overall equipment throughput. Cymer plans the commercialization of an EUV light source in 2009. Cymer continues to meet its EUV source development commitments to industry with burst power demonstrations of > 12 W in Q3 06, > 25 W in Q4 06, > 50W in Q2 07, and > 100 W in Q4 07. Current performance of our LPP development system is > 300 W 2 % bandwidth into 2π or > 100 W equivalent IF EUV output power within a 1ms burst at 50 kHz, continuous run times are in the range of hours and accumulate dose levels are reaching the MJ range.

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